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Analysis of Solar Spectral Irradiance Measurements from the SBUV/2-Series and the SSBUV Instruments

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NOAA-11 LONG-TERM CALIBRATION VIA SSBUV

The Solar Backscatter Ultraviolet, Model 2 (SBUV/2) instrument onboard the NOAA-11 satellite made daily solar spectral irradiance measurements between January 1989 and October 1994. While the measurements made by the SBUV-series instruments furnish an excellent data base for studies of solar UV variations, these instruments do not have an internal means to monitor and correct for long-term instrument sensitivity degradation, needed to evaluate solar cycle timescale irradiance change. The principal purpose of this work is to use yearly flights of the Shuttle SBUV/2 (SSBUV) instrument to maintain the long-term calibration of the NOAA-11 SBUV/2 instrument. During this period of performance we have begun updating the NOAA-11 SBUV/2 characterization and have further refined the SSBUV calibration, both steps which must be completed before the long-term calibration of the SBUV/2 can be completed. We have also performed a first attempt of the calibration transfer, demonstrating the viability of the transfer process. This work, summarized below, was presented at the Spring 1995 AGU meeting in Baltimore, Maryland.

The lighter curves shown in Figure 1 are time series of the NOAA-11 SBUV/2 solar spectral irradiance output for three wavelengths, normalized to the initial, or "Day 1" output. The heavy curves in this figure are estimates of long-term solar change, based on the Mg II proxy index model of DeLand and Cebula (1992). These curves demonstrate the existence of several significant problems in the long-term characterization of the NOAA-11 instrument, each of which will be addressed during the course of this research:

Uncorrected long-term degradation, ranging from approximately 2-5% for wavelengths longward of 300 nm to roughly 25% near 200 nm. The primary purpose of the SSBUV comparisons (demonstrated below) is to further evaluate and correct for this drift. The corrected NOAA-11 SBUV/2 data will then be used to assess long-term near UV solar variability during the period 1988 through 1994.

Approximate $\pm 1\%$ goniometric errors. Drift in the ascending node of the NOAA-11 spacecraft's orbit means that SBUV/2 solar data taken after 1992 were acquired outside of the range of the prelaunch goniometric calibration. We will extend the goniometric calibration using the solar data. Synergistic work performed on the NOAA-14 SBUV/2 instrument shows that instrument's goniometric calibration is significantly wavelength dependent at the shorter wavelengths. An investigation showed that the NOAA-11 goniometric calibration is also somewhat wavelength dependent. This dependence will be characterized and incorporated into the final version of the NOAA-11 SBUV/2 solar irradiance data set. This correction will result in an estimated 1% improvement in accuracy of the time series at wavelengths shortward of roughly 250 nm, and will most notably improve the accuracy of the instrument absolute irradiance values by as much as approximately 2% near 200 nm.

Wavelength drift and wavelength acquisition errors. The sweep mode wavelength scale of the NOAA-11 SBUV/2 instrument drifted by approximately 0.15 nm over the instrument's lifetime. In addition, commencing in 1992 the wavelength drive began to experience stability

problems in the sweep mode, with the result that the wavelength of a given data sample varied from scan to scan. Both of these problems must be dealt with in order to produce a precise and accurate long-term data set.

The next four figures demonstrate the viability and the current status of using comparisons with SSBUV to correct for long-term SBUV/2 instrument drift. Figure 2 presents spectral comparisons of the NOAA-11 SBUV/2 and SSBUV data for the period 1989 through 1993. Since the long-term accuracy of the SSBUV calibration is better than 2%, these curves confirm the drift in the SBUV/2 long-term calibration suggested in Figure 1. Figure 3 presents changes in the SBUV/2 sensitivity for three wavelengths, assessed via the SSBUV comparisons. Also shown are least-square linear regression fits to the data points. Note that the final correction of the SBUV/2 data, which will include comparisons with additional SSBUV Space Shuttle flights, may or may not remain completely linear with time. For these comparisons the SBUV/2 drift is assumed to be linear with time. Figure 3 shows that this assumption is valid to at least first order. The time and wavelength dependence of the drift is assessed via comparisons like those shown in Figures 2 and 3, with the result, shown in Figure 4, being the rate of change in the NOAA-11 instrument response as a function of wavelength. Also shown are the two sigma statistical confidence in the degradation parameters. (These errors somewhat underestimate the total error in the correction because they do not include, among other factors, the uncertainty introduced by the uncertainty in the long-term SSBUV calibration. The final NOAA-11 data product will include a detailed error assessment.) Presented in Figure 5 are time series of the NOAA-11 SBUV/2 solar irradiances for three wavelengths, where the data were corrected for long-term SBUV/2 instrument change using the Figure 4 result. Both solar rotation and longer term solar change are readily observed for the 205 nm time series. As expected, the magnitude of both the rotational and the longer term solar variations decrease by approximately a factor of two between 205 and 252 nm, and further decrease in the near UV. An approximate 1% quasi-step discontinuity and 1% goniometric errors remain, and will be dealt with in turn. The small (<1%) apparent increase in the 340 nm irradiance most likely indicates a slight overcorrection in the NOAA-11 degradation correction, which we hope to remove with further refinements to the both the SBUV/2 characterization and the long-term SSBUV calibration.

COMPARISONS WITH OTHER INSTRUMENTS

A second key area of this research is the comparison of the SSBUV and the NOAA-11 SBUV/2 solar spectral irradiance data with measurements from other instruments that monitor the solar spectrum in the middle ultraviolet. During this period of performance, SSBUV data from the ATLAS-1 (SSBUV-4, March 1992) mission were compared with data from the other two ATLAS UV solar irradiance instruments: SOLSPEC (Solar Spectrum Experiment) and SUSIM (Solar Ultraviolet Spectral Irradiance Monitor). Figure 6 presents the comparison of the mean solar irradiance measured by each of the three ATLAS solar instruments on 29 March 1992 to the irradiance measured by the other two ATLAS instruments, where a 5 nm running average has been applied to the data. Figure 7 presents a comparison of the irradiance measured by each instrument to the unweighted average of the three irradiance measurements. Both unsmoothed (1.1 nm resolution) and 5 nm-smoothed comparisons are shown. The ATLAS-1 SUSIM and SOLSPEC measurements

each agree with the SSBUV irradiance to within approximately $\pm 5\text{-}6\%$, but disagree with one another by as much as approximately 10%. The SSBUV irradiances approximately split the difference between the other two instruments, especially in the region between approximately 240 and 270 nm, where SOLSPEC and SUSIM instruments' data exhibit the largest differences. Similar, future comparisons of the ATLAS-2 and ATLAS-3 data from the three instruments are planned. This work will indicate whether the differences seen here between the three instruments on ATLAS-1 are due to systematic absolute calibration biases, calibration reproducibility problems, or errors in correcting these data for in-orbit instrument response variations.

While the agreement shown in Figure 7 is usually quite good, larger differences are noted, especially near the Mg II *h* and *k* doublet at 280 nm and the Mg I line at 285 nm. Each instrument team applies a detailed wavelength calibration to their data. However, small differences in the wavelength assigned to each instrument's solar spectrum can have a significant effect when spectra are compared. Especially problematic are the areas near solar absorption lines (e.g. the Mg II and Mg I lines), as well as regions where the solar spectrum makes large changes in magnitude (e.g. the Al and Mg edges). Each instrument has a slightly different bandpass width and slit function, further amplifying sensitivity to wavelength error. Shown in Figure 8 is a comparison of the average ATLAS-1 spectrum with a second spectrum formed by shifting the initial spectrum by 0.2 nm in order to demonstrate the sensitivity to wavelength determination error. The deviation of this shifted spectrum from the original spectrum approaches the size of the differences in the individual spectra. We have used several techniques to establish an accurate wavelength scale. Among these are comparison to high resolution solar spectra (Anderson and Hall, 1989), which can be determined with higher wavelength accuracy. For SSBUV no significant differences are noted between our internally-determined wavelength scale and the high resolution data to within the ± 0.02 nm precision of the comparison.

The mean ATLAS-1 solar spectrum is compared to mean UARS [the weighted average of the UARS SOLSTICE and SUSIM instruments (Woods et al., 1995)] solar spectrum for 29 March 1995 in Figure 9. Again both 1.1 nm instrument resolution and 5 nm smoothed comparisons are presented. The average ATLAS-1 and the average UARS solar spectra agree within $\pm 2.5\%$ over the common wavelength region, 200-350 nm. This excellent agreement is well within the estimated approximate 3-6% radiometric uncertainty in any one of the instruments. The agreement amongst these five instruments in the middle UV represents a significant improvement over historical comparisons. This improvement resulted from fastidious attention to preflight calibration and postlaunch characterization on the part of all experiment teams, supplemented by a rigorous NIST intercalibration campaign.

We have recently begun comparisons with GOME (Global Ozone Monitor Experiment) solar spectral irradiance data. Three preliminary versions of the initial GOME solar measurements were received and compared to a reference SSBUV solar spectrum. The purpose of these first comparisons is to assist the GOME investigators in assessing the state of their calibration and their data processing algorithm. In the region of overlap between the GOME and SSBUV data, 240-405 nm, the GOME solar irradiance values are, on average, approximately 5-10% smaller than the SSBUV irradiance values. Larger differences are observed shortward of 260 nm. During a meeting with GOME personnel held on 3-4 August 1995, detailed comparison results were presented, implications of the comparisons were discussed, and plans for further solar (and ozone) comparisons were formulated.

NOAA-14 SBUV/2: INITIAL OBSERVATIONS:

The fourth instrument in the SBUV/2 series was launched on the NOAA-14 satellite on 30 December 1994 and first observed the sun on 10 February 1995. The instrument is just now completing its Activation and Evaluation Phase and is expected to begin the Operational Phase of its mission in late August or early September 1995. Although the instrument has made near daily sweep mode measurements of the sun, it has yet to begin taking daily discrete mode data at the Mg II wavelengths. Discrete mode data are significantly less noisy than sweep mode data and are less susceptible to wavelength drift and wavelength drive errors than the sweep mode data. Discrete mode data are thus preferable to sweep mode data for use in constructing a Mg II proxy index (DeLand and Cebula, 1994). Commencing in May 1995 the NOAA-14 instrument began to experience significant wavelength drive errors, which, unfortunately are most serious near the Mg II doublet. Thus it is likely the NOAA-9 Mg II data will eventually need to be used to fill the gap between the NOAA-11 Mg II data (which ended on 16 October 1994 with the failure of the NOAA-11 diffuser deployment mechanism) and the yet-to-occur start of NOAA-14 Mg II solar observations. Unfortunately, there is a several month gap in the NOAA-9 discrete mode Mg II data beginning in late February 1995, thus NOAA-9 sweep mode data will have to be used for this period. (The NOAA-9 spacecraft was placed in a "safe mode" at the end of February, causing a loss of SBUV/2 volatile memory information. The SBUV/2 FLEX memory containing the Mg II wavelengths was not reloaded until summer 1995, thus no discrete mode Mg II data were taken during this period.) This will further complicate the construction of a long-term Mg II proxy index data set for the 1994-1995 period, and likely result in additional uncertainty in the accuracy of the index.

The NOAA-14 SBUV/2 instrument is unique in that it is the only instrument of the SBUV/2 series which was intercalibrated prelaunch with the SSBUV instrument. In August 1992 the SSBUV instrument was shipped to Ball Aerospace in Boulder, CO for refurbishment. During the next two months the NOAA-14 SBUV/2 and SSBUV instruments were intercalibrated via an exchange of calibration sources and fixtures. The two instruments' irradiance calibrations were found to agree at the 1-2% level. Shown in Figure 10 are comparisons of the initial NOAA-14 solar spectral irradiance with data from SSBUV, UARS SUSIM, and UARS SOLSTICE. Neglecting small, expected differences due to true solar variation, it is seen that the SBUV/2 data are systematically too low by approximately 4-8%. In light of the excellent agreement found during the prelaunch intercalibration, most surprising are the differences observed with the SSBUV data. The cause of these differences is unknown at present. The feature near 230 nm is probably due to a Wood's anomaly in the SBUV/2 instrument's sensitivity. The radiometric sensitivity of the NOAA-14 instrument was found to exhibit both absolute and spectral differences when the instrument was calibrated in air than when the instrument was calibrated in a vacuum. It is possible that further changes related to these air-to-vacuum differences have occurred, resulting in the biases seen in Figure 10. A second possibility is that the NOAA-14 SBUV/2 instrument's radiometric sensitivity degraded after the instrument's prelaunch calibration and before its initial solar observations.

Presented in Figure 11 are the initial NOAA-14 SBUV/2 sweep mode Mg II measurements, along with the corresponding preliminary UARS SUSIM Mg II index (D. Prinz, private communication)

data, and the scaled F10.7 cm index. Both Mg II indexes show the presence of approximate 13.5 day periodicity in February 1995. It is somewhat surprising to see such periodicity at this phase of the solar cycle, for it implies that two active regions are simultaneously present during the near solar minimum conditions. The F10.7 data also indicate the presence of two active regions. While these unscaled SUSIM and SBUV/2 data show excellent agreement in the February and March timeframe, in April the SBUV/2 Mg II index increases much more quickly than does the SUSIM index. This artifact is probably caused by errors in the NOAA-14 SBUV/2 wavelength drive system that, as noted previously, are largest near the wavelengths used to construct the Mg II index.

PRESENTATIONS AND PUBLICATIONS

Three papers, supported in part by this research grant and in part by NASA contract NAS5-31755, were presented at the American Geophysical Union 1995 Spring Meeting in Baltimore, Maryland during the current period of performance. Copies of those papers have been previously supplied under separate cover. We are presently preparing a manuscript on the ATLAS-1 three-instrument solar comparison for submission to Geophysical Research Letters. The contributions of R. P. Cebula to an under review Journal of Geophysical Research paper by Woods et al. were also supported by this research grant, and NASA sponsorship is acknowledged therein.

Cebula, R. P., M. T. DeLand, and E. Hilsenrath, NOAA-11 SBUV/2 Measurements of Solar UV Variations, *EOS Trans. Amer. Geophys. Union*, 76(17), Spring Meet. Suppl., S240, 1995.

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NOAA-11 SOLAR DATA

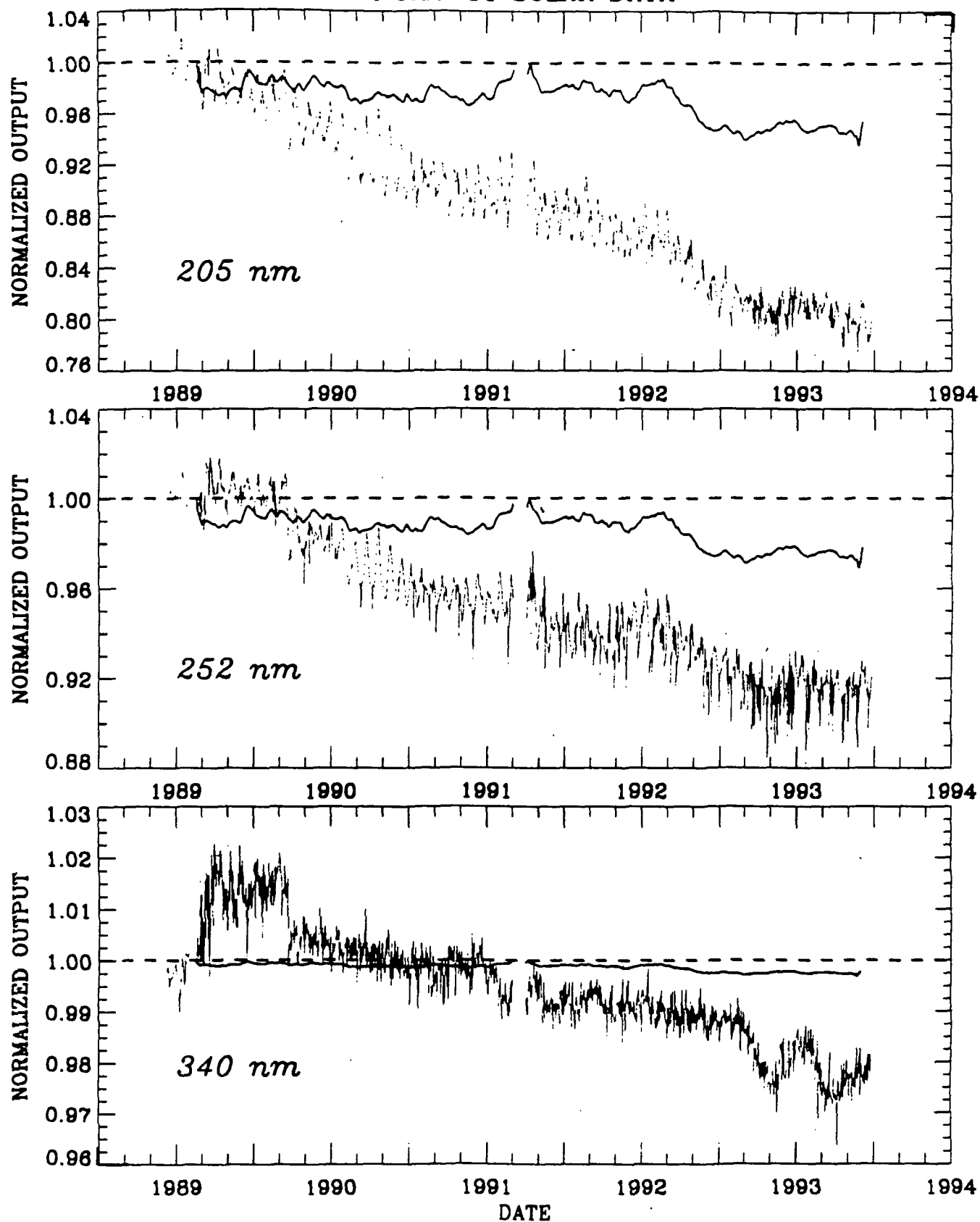


Figure 1

NOAA-11 OBSERVED SENSITIVITY CHANGE via SSBUV

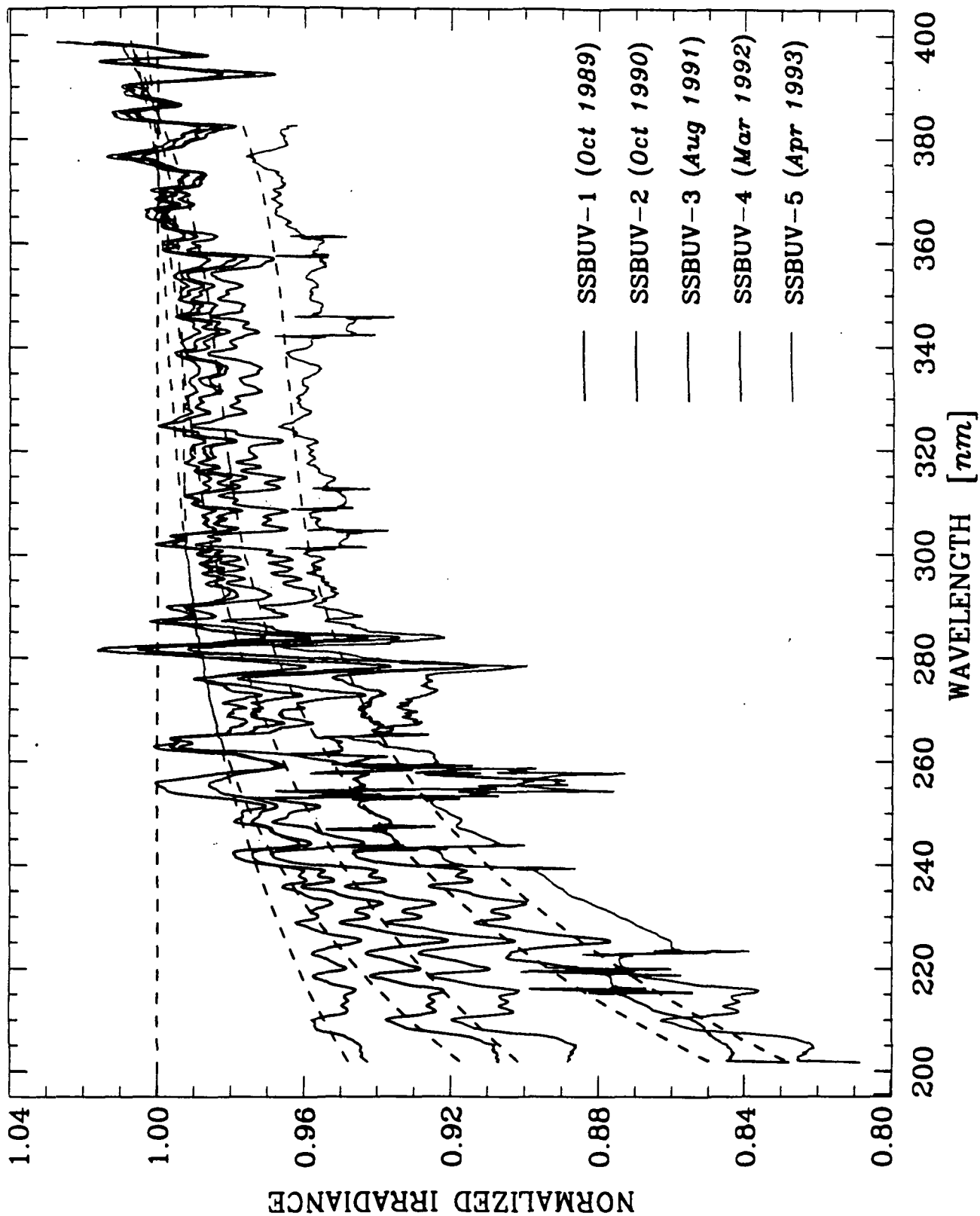


Figure 2

NOAA-11 CALCULATED SENSITIVITY CHANGE *via* SSBUV

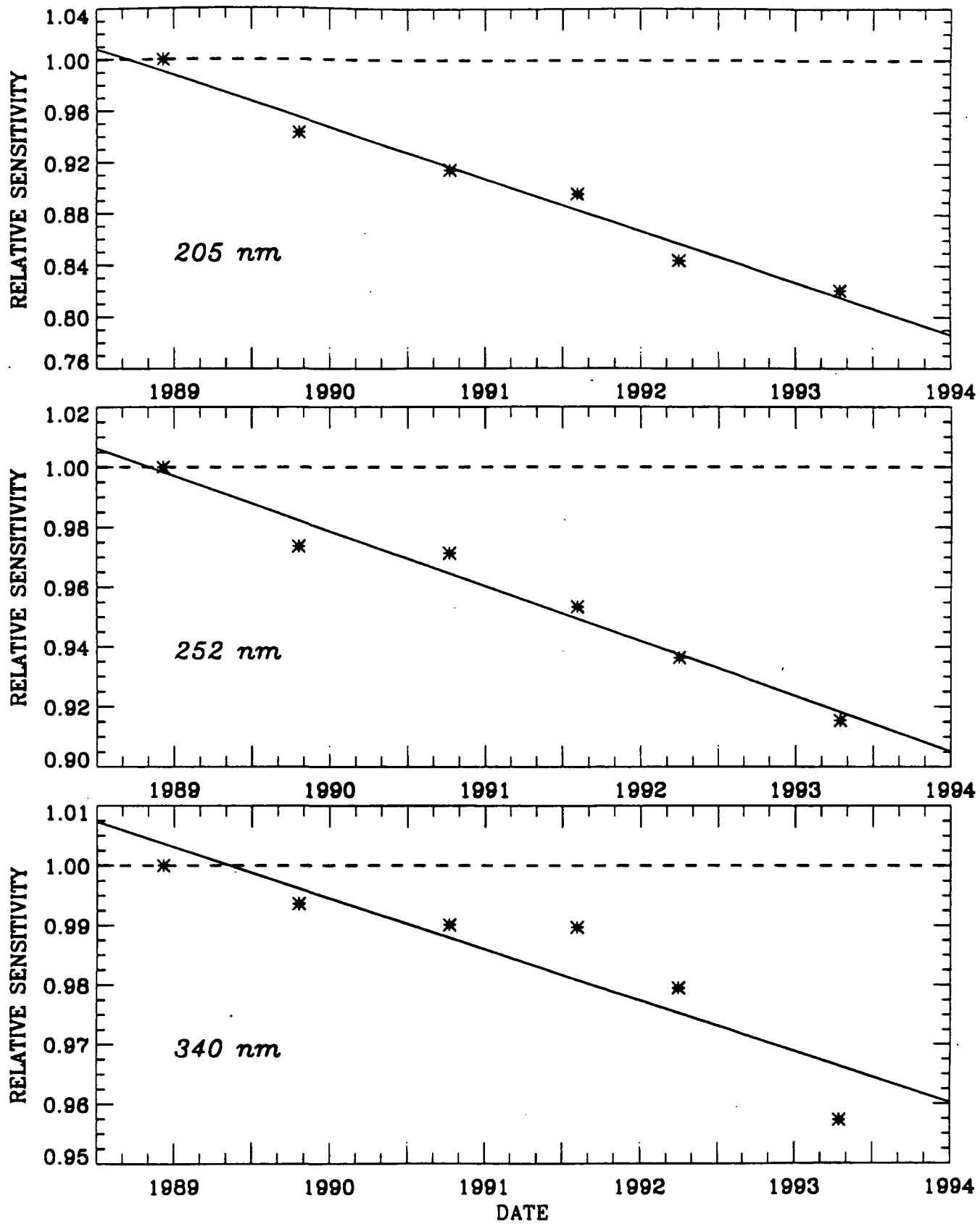


Figure 3

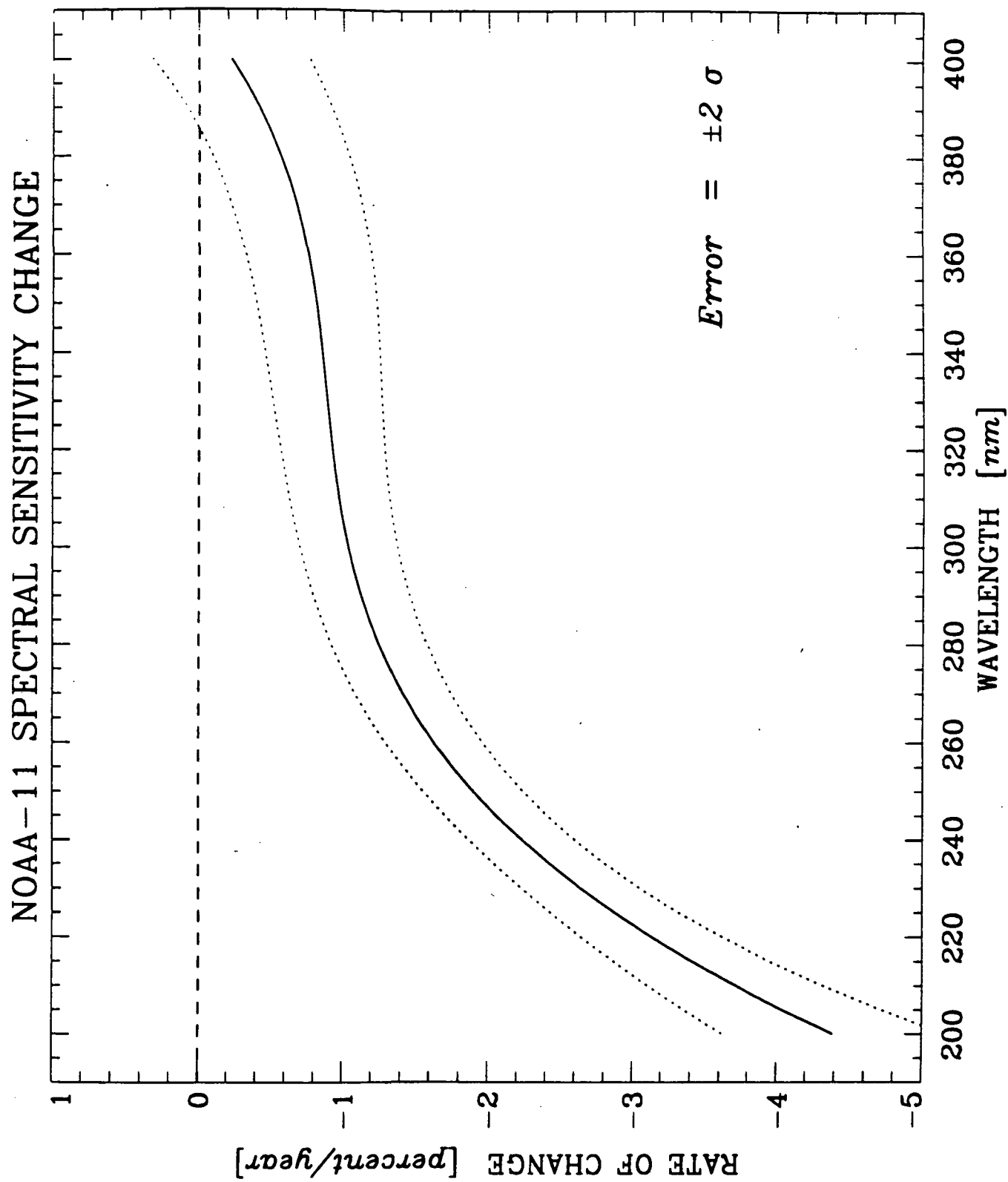


Figure 4

NOAA-11 MEASURED SOLAR CHANGE

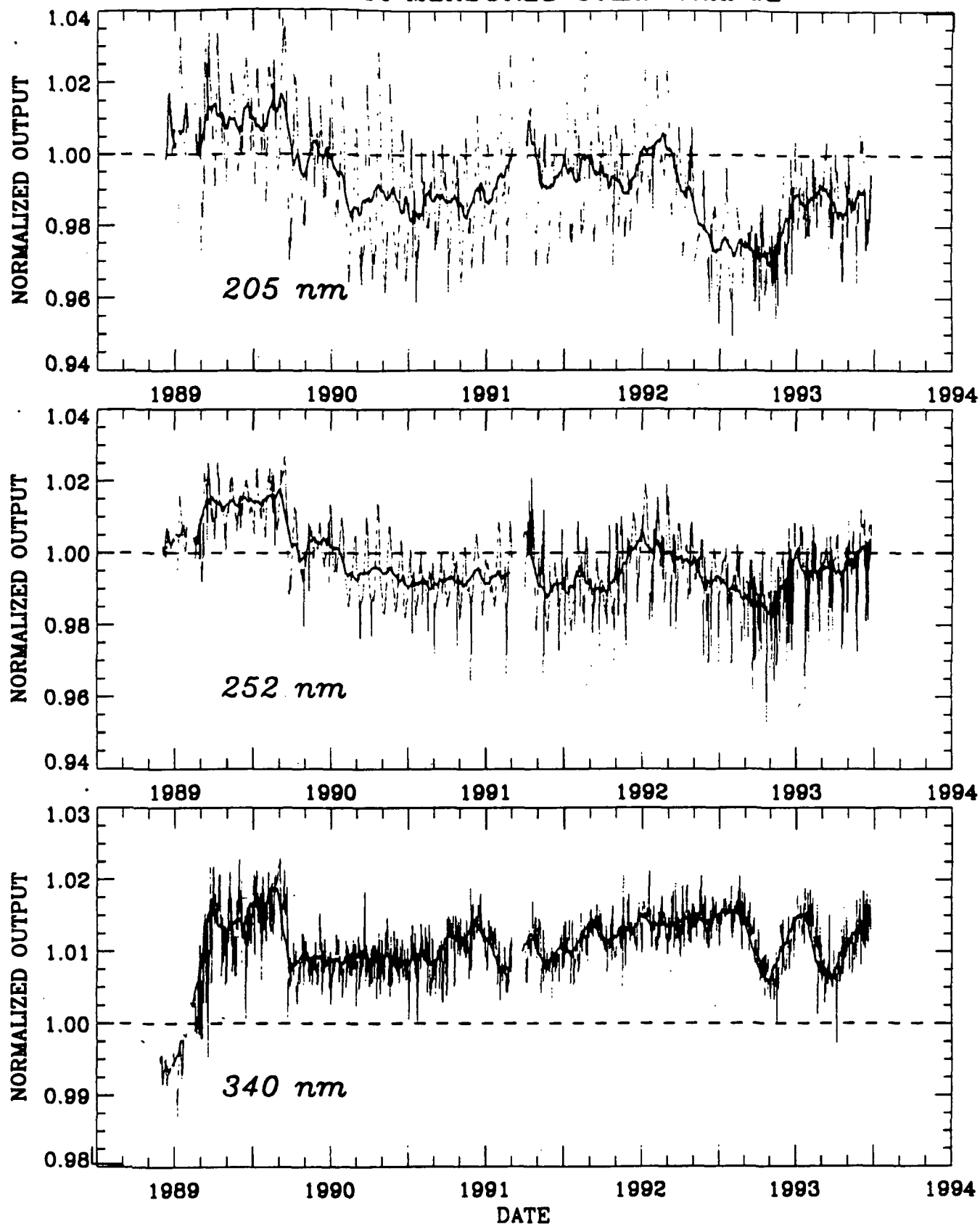


Figure 5

COMPARISON OF ATLAS-1 SOLAR IRRADIANCE MEASUREMENTS

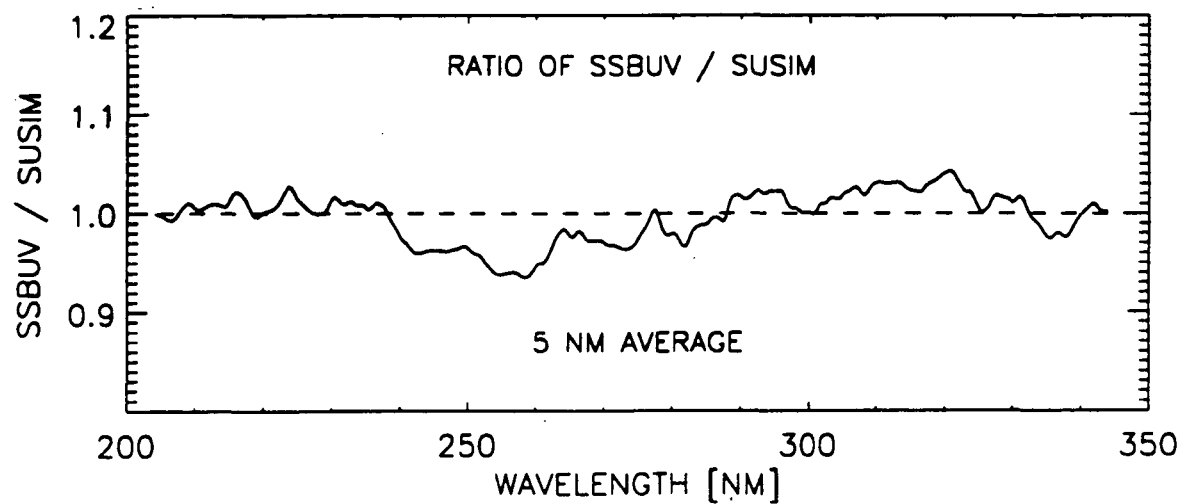
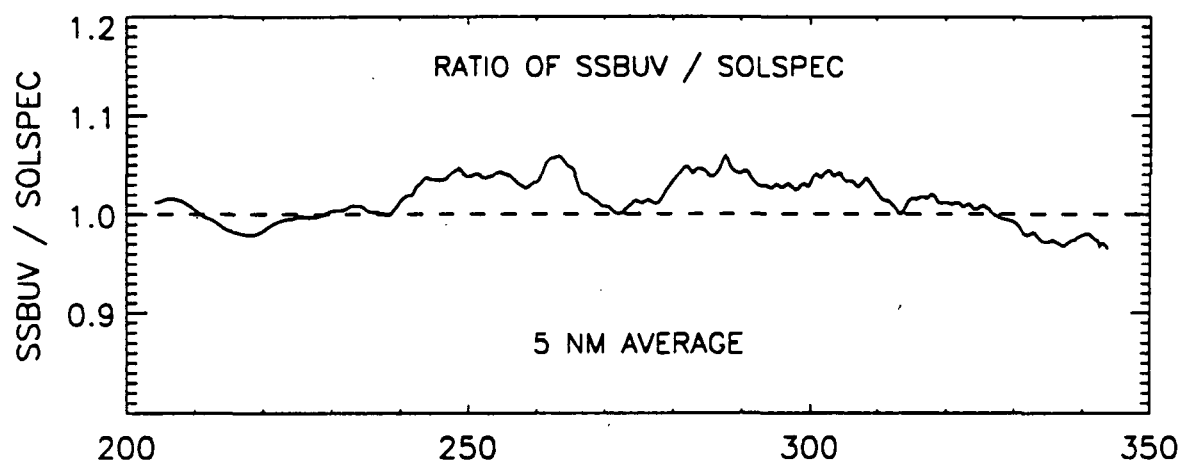
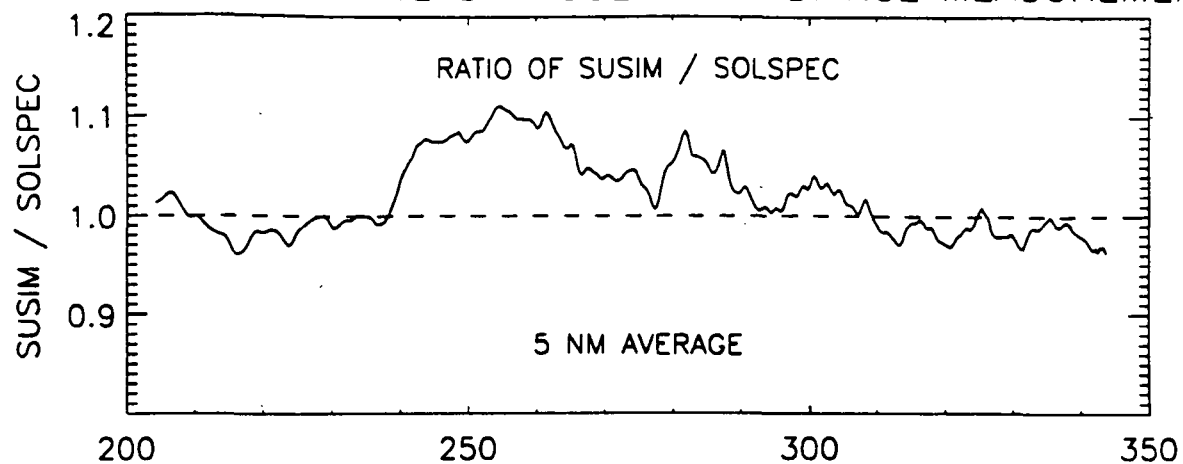


Figure 6

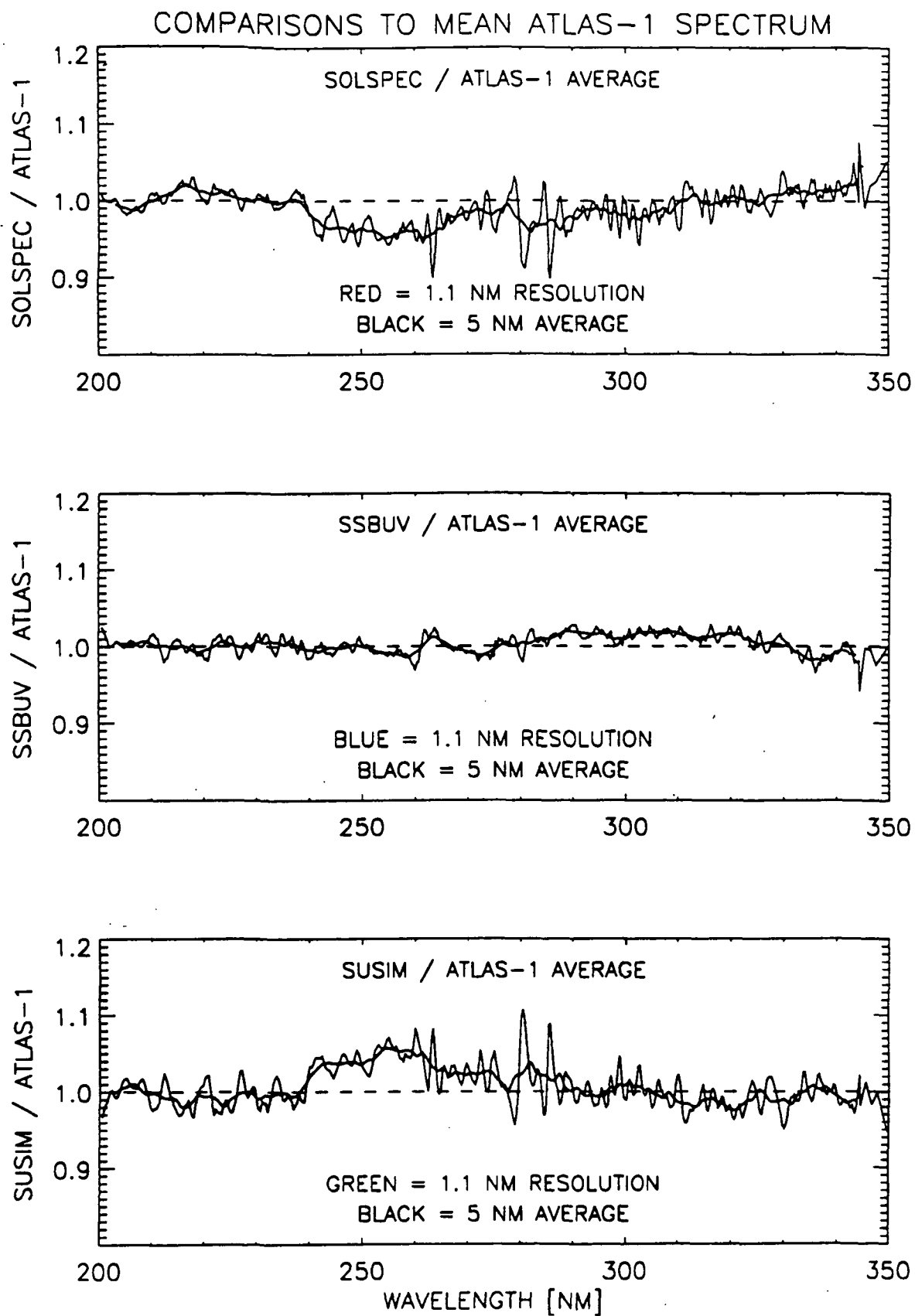


Figure 7

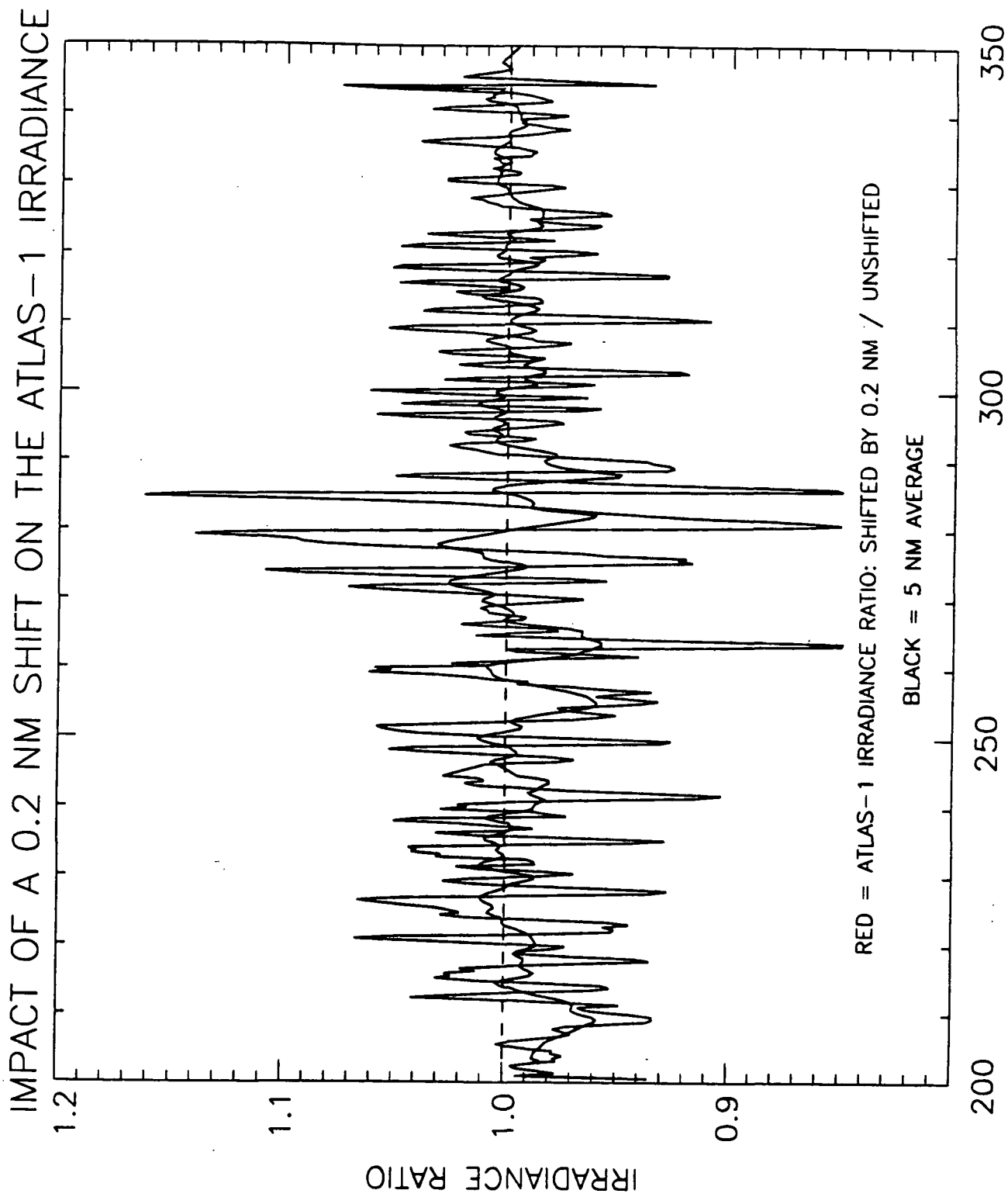


Figure 8

ATLAS-1 & UARS SOLAR SPECTRAL IRRADIANCE COMPARISON

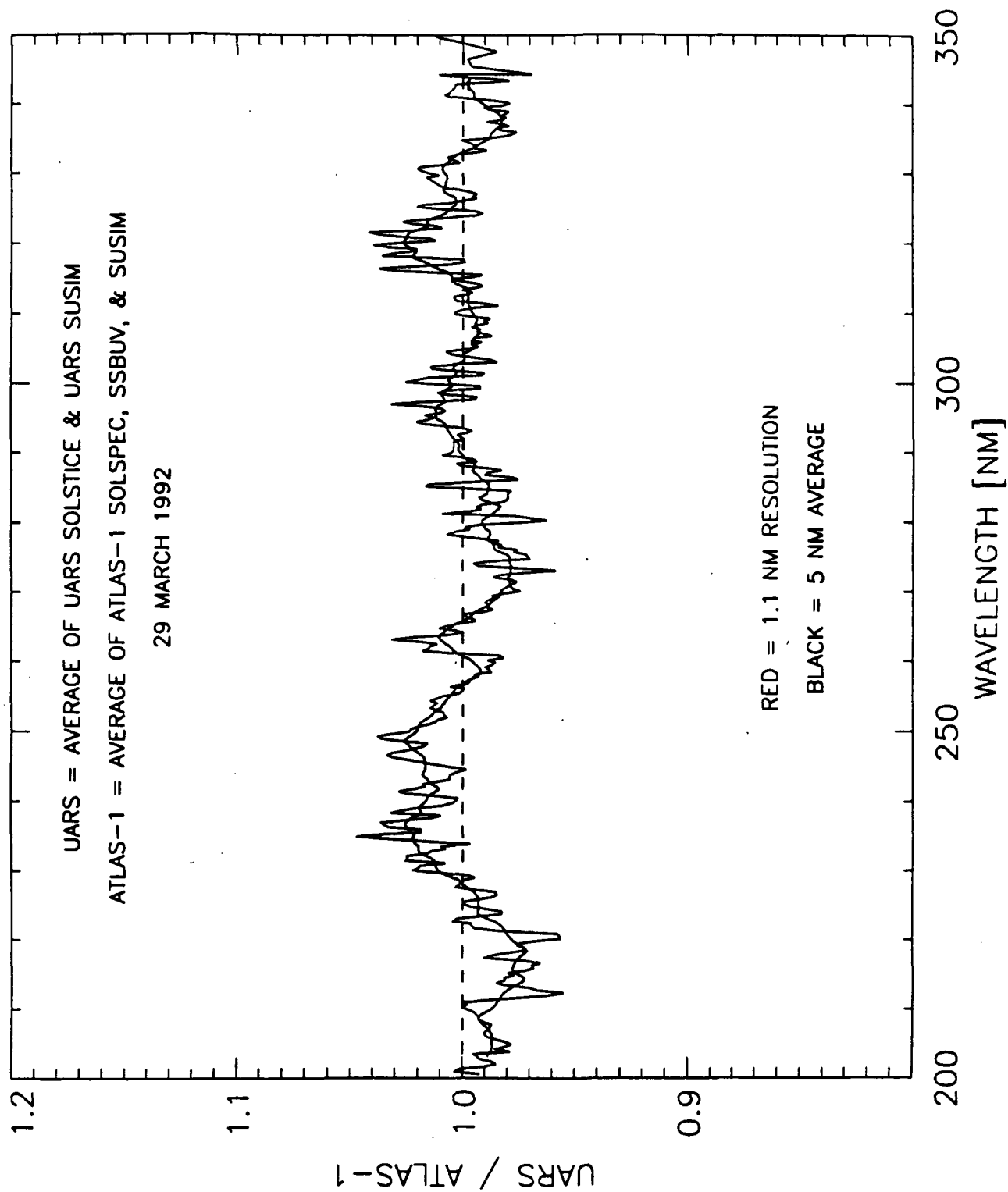


Figure 9

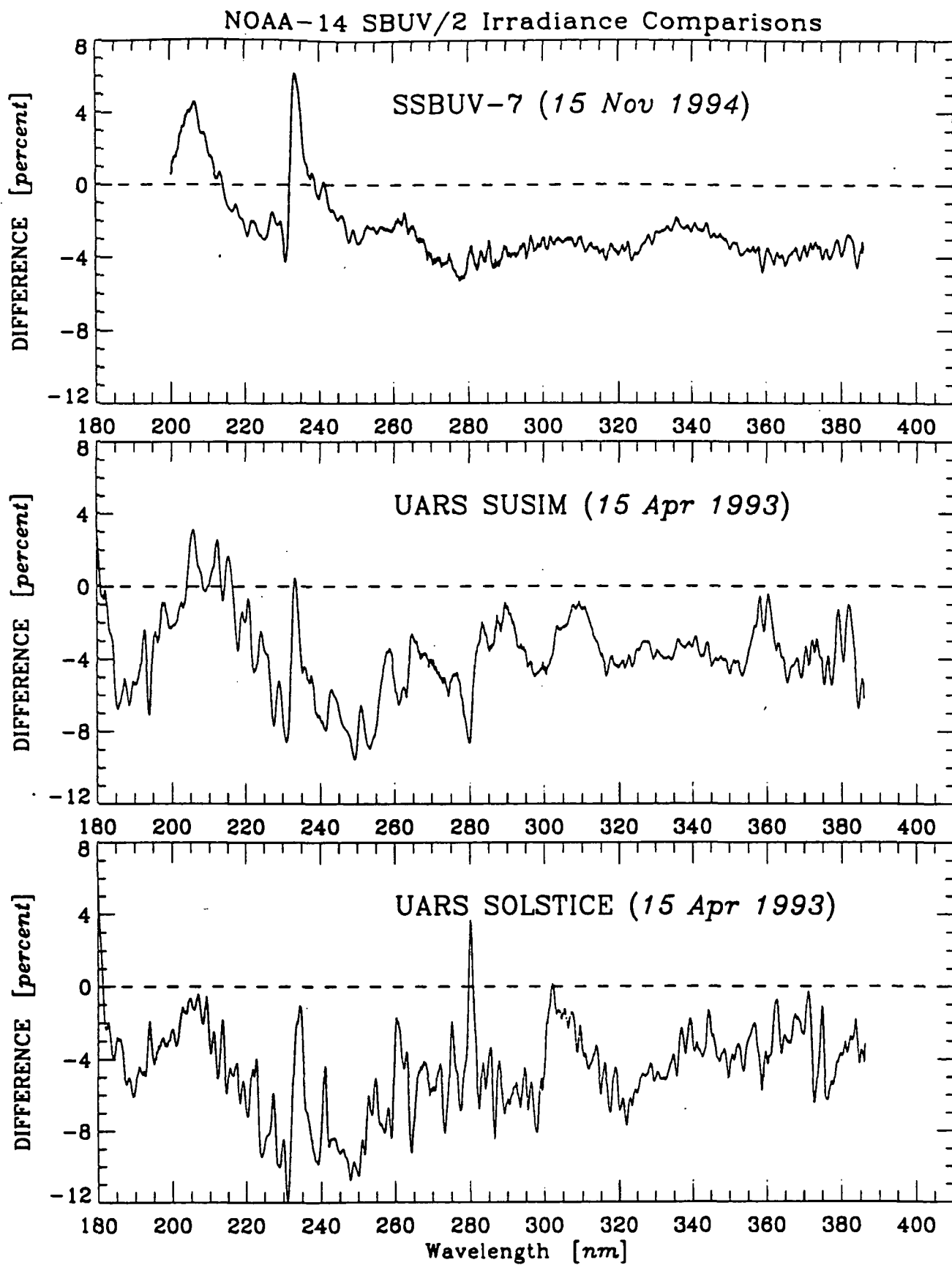


Figure 10

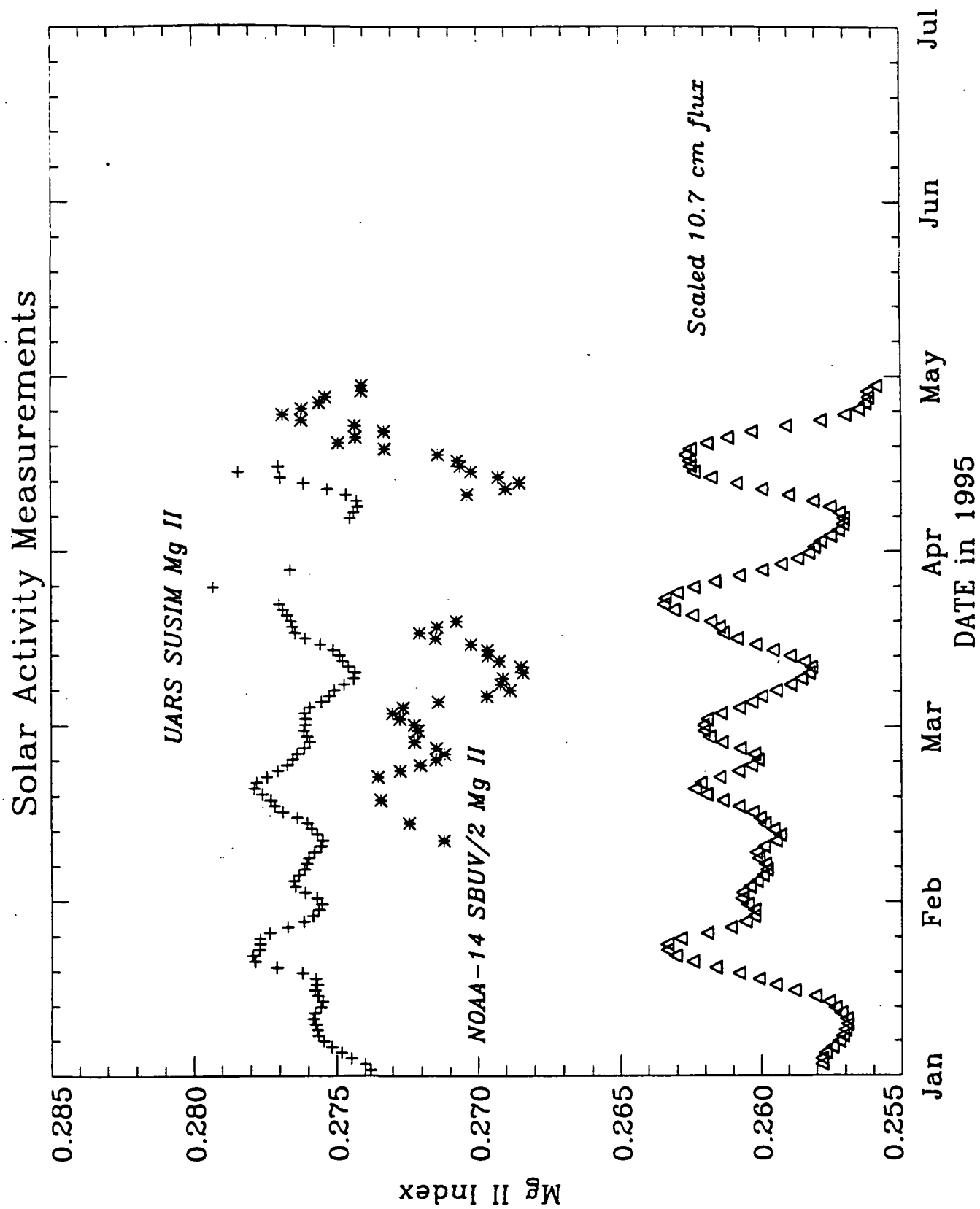


Figure 11